A BeppoSAX view of transient black hole candidates in quiescence

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Abstract. We report on BeppoSAX observations of five transient black hole candidates during their quiescent phase. We confirm these sources are X–ray faint, improving on and complementing existing upper limits. We derive 1–10 keV upper limits for GRO J0422+32, GRS 1009–45, 4U 1630–47 and XTE J1748–288, which range from 2×10^{32} erg s^{-1} to 5×10^{34} erg s^{-1}. We positively detect GS 2023+338. Its X–ray spectrum can be fit by a power law (photon index $\Gamma = 1.9$) or a thermal bremsstrahlung (with $k\,T_{\rm br} = 7$ keV), converting in both cases to a 1–10 keV unabsorbed luminosity of $\sim 10^{33}$ erg s^{-1}. These values are comparable to the ones derived during an ASCA observation in 1994, indicating that the source remains stable over a ~ 5 yr baseline.

1. Introduction

Transient black hole binaries are characterised by bright outbursts lasting up to several months and recurring every 1–100 yr (with a clear preference for long recurrence times). In between these outbursts, sources are quiescent with very low X–ray luminosities. At the present time only five transient Black Hole Candidates (BHCs) have been detected in quiescence and upper limits exist for six other systems (Asai et al. 1998; Menou, Narayan & Lasota 1999a; Campana & Stella 2000; Garcia et al. 2001).

A 0620–00 was the first BHC to be detected in quiescence. Despite the small number of photons collected in the ROSAT observation the spectrum was determined to be soft. A 0.5–10 keV luminosity of $L_X \sim 10^{31}$ erg s^{-1} (for a distance of $d = 1.2$ kpc) was obtained by extrapolating the ROSAT data (McClintock et al. 1995). Chandra detected the source at a level ~ 10 times lower (Garcia et al. 2001). GS 2023+338 (V 404 Cyg) was observed with ASCA at a 0.5–10 keV luminosity of $L_X \sim 2 \times 10^{33}$ erg s^{-1} ($d = 3.5$ kpc; Narayan, Barret & McClintock 1997). The spectrum is well fit by a power law with photon index $\Gamma \sim 2.1^{+0.5}_{-0.3}$ or by a thermal bremsstrahlung with an equivalent temperature of $k\,T_{\rm br} = 4.6^{+3.6}_{-1.5}$ keV. Analysing the

same dataset Asai et al. (1998) obtained $\Gamma = 1.7^{+0.3}_{-0.2}$. Finally, GRO J1655–40 was detected again by ASCA at $L_X \sim 2 \times 10^{32}$ erg s^{-1} ($d = 3.2$ kpc; Hameury et al. 1997). The spectrum could be described by a power law model with a quoted index $\Gamma \sim 1.5 \pm 0.6$ (Hameury et al. 1997). Asai et al. (1998) analysed the same dataset and found $\Gamma = 0.7^{+2.1}_{-0.4}$. Chandra observed this source when it was a factor of ~ 10 (Garcia et al. 2001).

Since the discovery of their low X–ray quiescent luminosity, the study of BHCs in quiescence has attracted attention because this emission might be able to distinguish them from quiescent neutron star systems (for a review see Campana et al. 1998a). At the very beginning, Tanaka & Shibazaki (1996) argued that BHCs and neutron stars systems at low luminosities show similar soft spectra, well approximated by a single temperature black body ($k\,T_{\rm bb} \sim 0.2 - 0.3$ keV). This was based (and biased) on ROSAT results and only on a single BHC (A 0620–00). ASCA and BeppoSAX observations led to the discovery of hard tails in neutron star systems (Asai et al. 1996, 1998; Campana et al. 1998b, 2000) as well as the detection of non-thermal spectra in GS 2023+338 and GRO J1655–40, challenging this picture (however, GS 2023+338 and GRO J1655–40 have orbital periods longer than the great majority of low mass transients and, therefore, likely experience a higher time-averaged mass exchange rate). In a recent paper, Garcia et al. (2001) reported on deep Chandra observations of black hole transients in quiescence, detecting two new sources with short orbital period (GRO J0422+32 and GS 2000+25). Now three short orbital period BHCs

Table 1. Summary of BeppoSAX observations.

Source	LECS Exp. time (s)	MECS Exp. time (s)[*]	PDS Exp. Time (s)	Observation number
GRO J0422+32	19681	46274 (2)	21275	20535001
GRS 1009–45	19773	40675 (2)	20689	20607001
4U 1630–47	13357	32944 (3)	22426	20315001
GS 2023+338	–	21384 (3)	10098	20303001
XTE J1748–288[+]	19174	47884 (2)	34787	20130002

[*] in parenthesis the number of MECS active units.
[+] source at 5′ off-axis.

have been detected all with 0.5–10 keV luminosities in the $2 - 8 \times 10^{30}$ erg s^{-1} range. These data confirm that black hole transients in quiescence are much less luminous than the corresponding neutron star transient systems *in X–rays*.

Advection dominated accretion flow (ADAF) models have become popular in explaining the low luminosity of quiescent BHCs as well as their spectral energy distribution (Narayan et al. 1996; Narayan, Garcia & McClintock 1997; Menou et al. 1999a, 1999b). In these models a large fraction of the gravitational energy is advected into the black hole, therefore lowering considerably the radiative efficiency of the accretion process. Observations show that the ratio of minimum X–ray luminosity in quiescence to maximum X–ray luminosity in outburst is significantly smaller (a factor of about 100) in black hole transients than in and neutron star transients (Narayan et al. 1997; Garcia et al. 1998; Garcia et al. 2001). Campana & Stella (2000) noted that in the latest ADAF models the optical/UV luminosity derives from synchrotron radiation produced by the ADAF itself and therefore must be included in the luminosity budget. Ascribing the bulk of the residual optical/UV flux to the ADAF removes much of the difference in luminosity swing between black hole and neutron star transients, weakening one of the main drives of ADAF models. Possible ways out are that a large fraction of the accreting matter is stopped/evaporated at the outer disk boundary with only a very small fraction leaking towards the compact object and/or ADAFs do not contribute to the optical luminosity as in the older ADAF models (Campana & Stella 2000).

In this paper we present a comprehensive view of black hole transients in quiescence observed with the Italian/Dutch satellite BeppoSAX complementing and improving current upper limits and existing spectra. In Section 2 we describe the data set and analysis. In Section 3 we discuss the results.

2. Observations and data reduction

We present the results of the observations of black hole transients in quiescence carried out with the BeppoSAX satellite (Boella et al. 1997a). We analysed the data from the Low Energy Concentrator Spectrometer (LECS; 0.1–10 keV, Parmar et al. 1997a) and the Medium Energy Concentrator Spectrometer (MECS; 1.3–10 keV, Boella

et al. 1997b). As usual, LECS data were collected only during satellite night-time leading to shorter exposure times. Upper limits in the hard X–ray band were obtained with the Phoswich Detector System (PDS, 15–300 keV; Frontera et al. 1997). The PDS collimators rocked on and off the target in order to monitor the background. This also resulted in a shorter exposure time than the MECS.

BeppoSAX observed four BHCs in quiescence: GRO J0422+32, GRS 1009–45, 4U 1630–47 and GS 2023+338. XTE J1748–288 was serendipitously observed during a pointing toward the Galactic Center region. For a summary of the observations see Table 1.

The BeppoSAX images were searched for sources at the position of the BHCs' optical counterpart. Only one out of five BHCs was detected (GS 2023+338) confirming the elusiveness of this kind of source in quiescence.

Upper limits for imaging instruments were determined counting the number of events within a specified box (4′ radius), correcting those counts for vignetting, exposure and point spread function and comparing them with the number of events in an outer background box free of sources. In the case of the PDS collimators source upper limits were derived by comparing the number of events collected on and off the the source.

GRO J0422+32 was observed by BeppoSAX on September 2, 1998, about 2,200 days after the previous outburst. The source was not detected and we place a $3\,\sigma$ upper limit of 2×10^{-3} c s^{-1} on the MECS count rate, which translates to a flux limit of 1.5×10^{-13} erg s^{-1} cm^{-2} (2–10 keV), assuming a power law spectrum with photon index $\Gamma = 2.1$ (the same as observed in GS 2023+338 in quiescence; Narayan et al. 1997) and the galactic column density in the direction of the source $N_H = 1.7 \times 10^{21}$ cm^{-2}. For a distance of 3.6 kpc (Shrader et al. 1994) we obtain an upper limit on the 2–10 keV luminosity of 2×10^{32} erg s^{-1}. This is to be compared with the value derived by Garcia et al. (1998) of 4×10^{31} erg s^{-1} (0.5–10 keV) which was obtained by extrapolating over a much larger energy range the result of a deep ROSAT-HRI pointing. The BeppoSAX PDS data give an upper limit of $\sim 6 \times 10^{-12}$ erg s^{-1} cm^{-2} in the 15–50 keV energy band, which translates to $\sim 9 \times 10^{33}$ erg s^{-1}.

4U 1630–47 was observed on March 26, 1997, about one year after the 1996 outburst (this source in contrast with other transient BHCs shows recurrent outbursts, Parmar, Angelini & White 1995). The $3\,\sigma$ upper limit
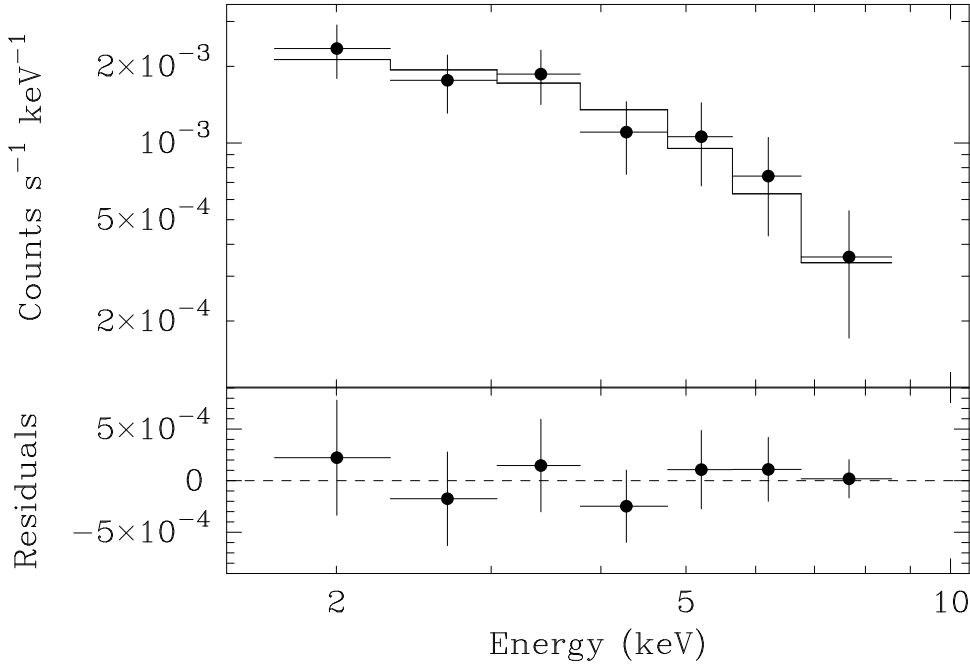
Fig. 1. X–ray spectrum of GS 2023+338 in quiescence. The spectrum is fit with an absorbed power law model. In the lower panel the ratio between the data and the model is presented.

on the MECS count rate amounts to 1.2×10^{-3} c s^{-1}. This translates into an upper limit on the 2–10 keV unabsorbed luminosity of 2×10^{33} erg s^{-1} for a distance of 10 kpc, a power law with $\Gamma = 2.1$ and $N_H = 8 \times 10^{22}$ cm^{-2} (Oosterbroek et al. 1998). Even if this upper limit is in the range of those previously obtained with the ROSAT-HRI (8×10^{33} erg s^{-1} 0.2–2.4 keV) and ROSAT-PSPC (7×10^{32} erg s^{-1} 0.2–2.4 keV; Parmar et al. 1997b), the more extended energy range of the MECS makes the BeppoSAX limit less affected by interstellar absorption. At high energies, the PDS limit on the 15-50 keV flux was of $\sim 9 \times 10^{-11}$ erg s^{-1} cm^{-2} (corresponding to $\sim 1 \times 10^{36}$ erg s^{-1}). This relatively high value is due to the presence of a number of sources in the PDS field of view, which are clearly seen in the MECS.

GRS 1009–45 was observed on December 3, 1998, about 1,900 days after the previous outburst. We obtain a 3σ upper limit of 1.6×10^{-3} c s^{-1} on the MECS count rate. This translates into an upper limit of 1×10^{33} erg s^{-1} on the 2–10 keV unabsorbed luminosity for a distance of 3 kpc (Della Valle et al. 1997), a power law with $\Gamma = 2.1$ and $N_H = 10^{21}$ cm^{-2}. The 15–50 keV upper limit from the PDS amounts to $\sim 7 \times 10^{33}$ erg s^{-1}. No previous upper limits exist on the 2–10 keV and 15–50 keV luminosities.

XTE J1748–288 was observed on April 5, 1997, about 400 d before its discovery. We obtain a 3σ upper limit on the MECS count rate of 6×10^{-3} c s^{-1}. Despite the relatively long exposure, this fairly high value is due to the source position right on the MECS "strongback" (Boella

et al. 1997b). Using the appropriate response matrix we derive a flux of $< 6 \times 10^{-12}$ erg s^{-1} cm^{-2} (i.e. $< 5 \times 10^{34}$ erg s^{-1} at 8.5 kpc). No upper limits in the 15–50 keV energy band can be set due to the presence of strong sources in the field.

In passing we note that GX 339-4 has been observed and detected by BeppoSAX at a level of $\sim 6 \times 10^{33}$ erg s^{-1} (Kong et al. 2000). This luminosity level is high when compared with the other BHCs, suggesting that the observed 'off'-state of GX 339-4 may not correspond to the quiescent state of a transient system (note also that GX 339-4 is usually considered a persistent source). Another interesting system monitored by BeppoSAX is CI Cam (XTE J0421+560). This source was observed three times in quiescence (156, 541 and 690 d after the latest outburst, respectively) with very different outcomes: i) a very soft spectrum ($\Gamma \sim 4$) with a low column density ($N_H \sim 10^{21}$ cm^{-2}) and a 1–10 keV luminosity of 2×10^{32} erg s^{-1} (at 2 kpc); ii) a hard spectrum ($\Gamma \sim 2$) with a high column density ($N_H \sim 4 \times 10^{23}$ cm^{-2}) and a luminosity of 4×10^{33} erg s^{-1}; iii) undetected with an upper limit of 4×10^{32} erg s^{-1} (Parmar et al. 2000). However, the nature of the compact object of CI Cam is presently unclear.

2.1. Spectral analysis: GS 2023+338

The source spectrum of GS 2023+338 was extracted from the MECS data within a radius of $4'$ centered on the source

position (LECS data were unavailable). We collected 433 photons within the full energy range. Background subtraction was performed using the standard background files. We used the publicly available calibration files at 2000 January and XSPEC 11.0. We rebinned the MECS spectrum in order to have at least 50 photons per spectral bin, resulting in seven bins. The lack of the LECS data forced us to adopt a value for the absorbing column density. Following Wagner et al. (1994) and Narayan et al. (1997) we used a value of $N_H = 10^{22}$ cm^{-2}. With this value of the column density a power law model provides an adequate description of the data with a photon index $\Gamma = 1.9^{+0.6}_{-0.5}$ (errors at 90% confidence level for one parameter of interest) with a $\chi^2_{\rm red} = 0.2$ (for 5 d.o.f.). A bremsstrahlung model provides also a good fit with $kT_{\rm br} = 6.9^{+31.5}_{-3.7}$ keV and $\chi^2_{\rm red} = 0.3$. A black body model instead fails to successfully describe the spectra with $\chi^2_{\rm red} = 1.4$ ($kT_{\rm bb} = 1.0^{+0.3}_{-0.2}$ keV). This last model can be reconciled with the data only by assuming a very low column density (formally null) and $kT_{\rm bb} = 1.1^{+0.1}_{-1.1}$ keV ($\chi^2_{\rm red} = 1.1$). The unabsorbed 1–10 keV flux as derived with the power law model amounts to 7.1×10^{-13} erg s^{-1} cm^{-2}. This is to be compared with the 8.2×10^{-13} erg s^{-1} cm^{-2} value derived from the ASCA observation (Narayan et al. 1997). The 1–10 keV unabsorbed luminosity is $L_X = 1.2 \times 10^{33}$ erg s^{-1} (at 3.5 kpc). The PDS provides an upper limit to the 15–50 keV luminosity of $\sim 3 \times 10^{34}$ erg s^{-1}.

3. Conclusions

We report on the BeppoSAX view of transient BHCs in quiescence. We further confirm that BHCs in quiescence are X–ray faint with luminosities below $\sim 10^{32} - 10^{33}$ erg s^{-1} (at which neutron star transients are usually detected) and reporting for the first time upper limits in the 2–10 keV energy band for four sources GRO J0422+32, GRS 1009–45, 4U 1630–47 and XTE J1748–288. These limits improve and confirm existing extrapolations from lower energy bands (mainly ROSAT, 0.1–2.4 keV). Moreover, we quote the upper limits in the hard energy band 15–50 keV derived from the PDS data. These hard X–ray luminosity limits might be useful to constrain ADAF models, for which high energy tails are expected (current models easily satisfy these constraints, e.g. Menou, Narayan & Lasota 1999a). After the failure of ASTRO-E, these limits will remain unrivaled for years to come.

One exception to the above cases, that was confirmed also by BeppoSAX observation, is GS 2023+338 revealed at a level of $\sim 10^{33}$ erg s^{-1} (1–10 keV). The GS 2023+338 luminosity derived is at a level and with a spectrum similar to those of the ASCA observation five years before (Asai et al. 1998; Hameury et al. 1997). This indicates that, within the uncertainties, the spectrum and the flux level of GS 2023+338 in quiescence remains fairly constant.

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